# The Imaging X-ray Polarimeter (IXPE)
# Part 1

Martin C. Weisskopf
on behalf of the IXPE Science Team
NASA/MSFC (Emeritus)

Presentation to a UAH Seminar, 14 Feb, 2023

# *The IXPE Team*

| | |
|---|---|
| **NASA Marshall Space Flight Center** – PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving | **IAPS, INAF (Istituto Nazionale di Astrofisica / National Institute for Astrophysics), INFN, OAC, OHB Italia** – Polarization-sensitive imaging detector systems |
| | **CU LASP** – Mission operations |
| **ASI (agenzia spaziale italiana)** – Detector system funding, ground station | **Roma Tre (Università degli Studi), Stanford University** – Scientific theory |
| | **Nagoya University** – Thermal shields |
| **Ball** – Spacecraft, payload structure, payload, observatory I&T | **MIT (Massachusetts Institute of Technology)** – Co-Investigator |

**Science Advisory Team**

**SAT currently comprises > 175 scientists from 13 countries**

# IXPE Mission Description

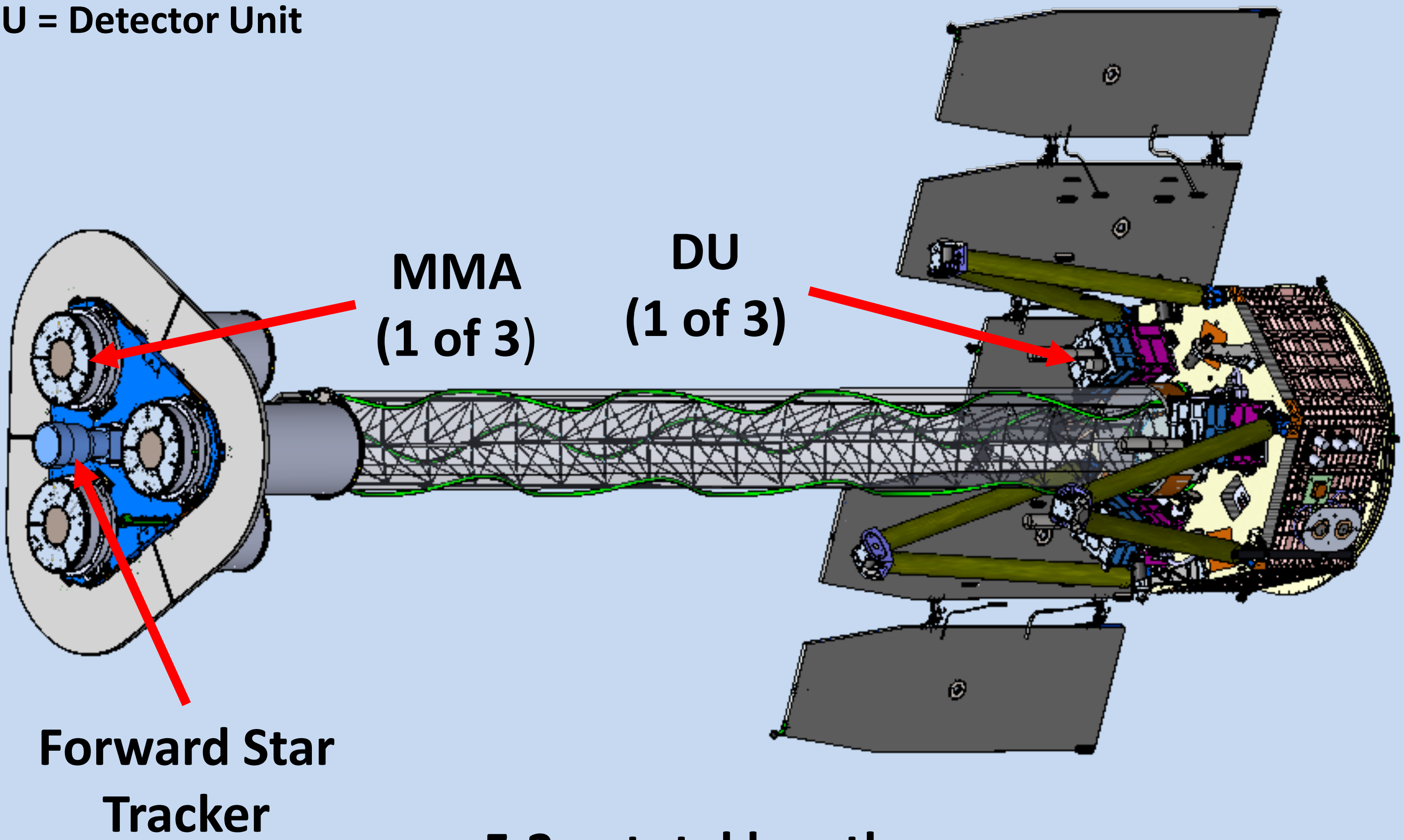
- Launched 2021 December 9, on a Falcon 9 from KSC
- 600-km circular orbit at a nominal 0° inclination
- 2-year baseline mission, optional extension with GO program
- Point and stare (with dither) at pre-selected targets
- Malindi ground station - primary (Singapore - secondary)
- Mission Operations Center (MOC) at the University of Colorado, Laboratory for Atmospheric and Space Physics (LASP)
- Sciences Operations Center (SOC) at MSFC
- Data archiving at NASA's HEASARC
  - During the first 3 months of the mission, including orbital checkout, all IXPE data shall be made publicly available at the HEASARC within 30 days of the end of an observation.
  - After the first 3 months of the mission, data shall be made available to the HEASARC within 1 week of the end of an observation

# Launch 1:00 AM December 9, 2021

**Equatorial Orbit**
**600 km altitude**

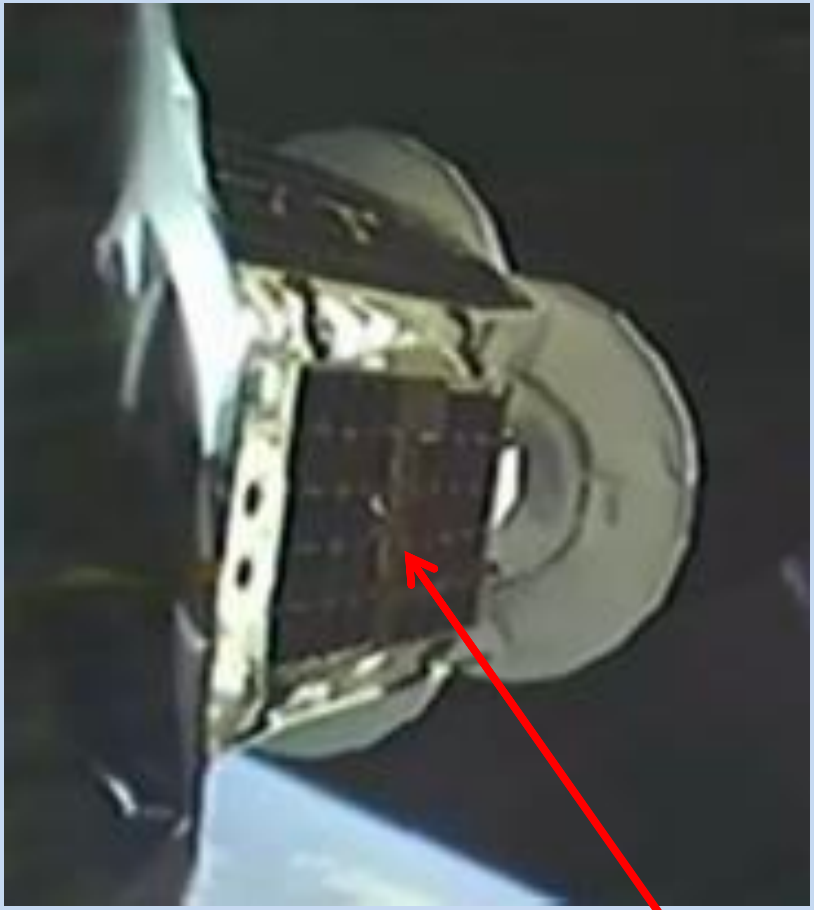
# *IXPE DEPLOYED*

**MMA = Mirror Module Assembly**
**DU = Detector Unit**

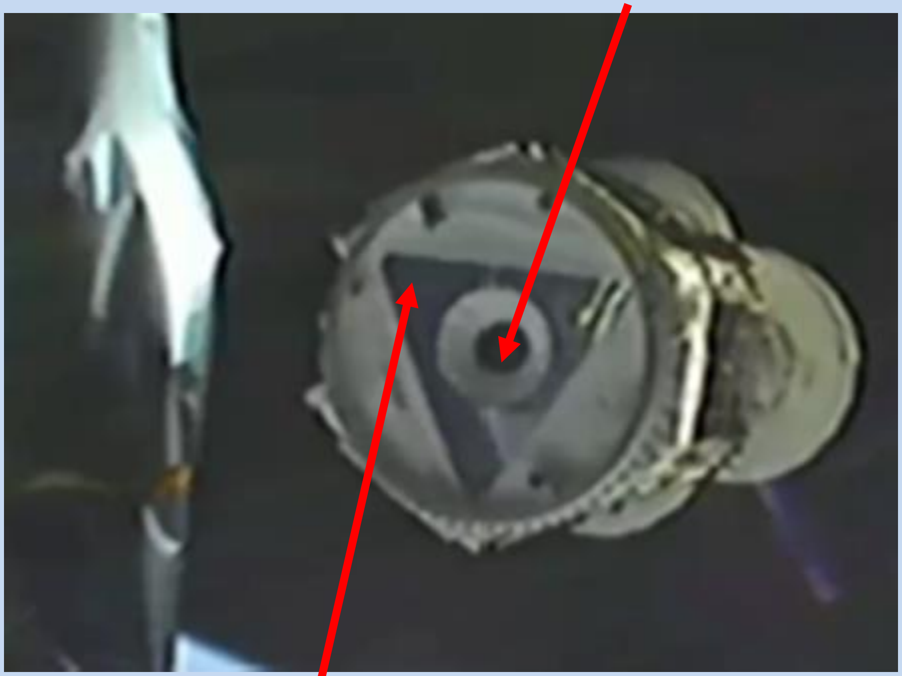



**5.2 m total length**
**4.0 m focal length**

# *Release from the Falcon 9*



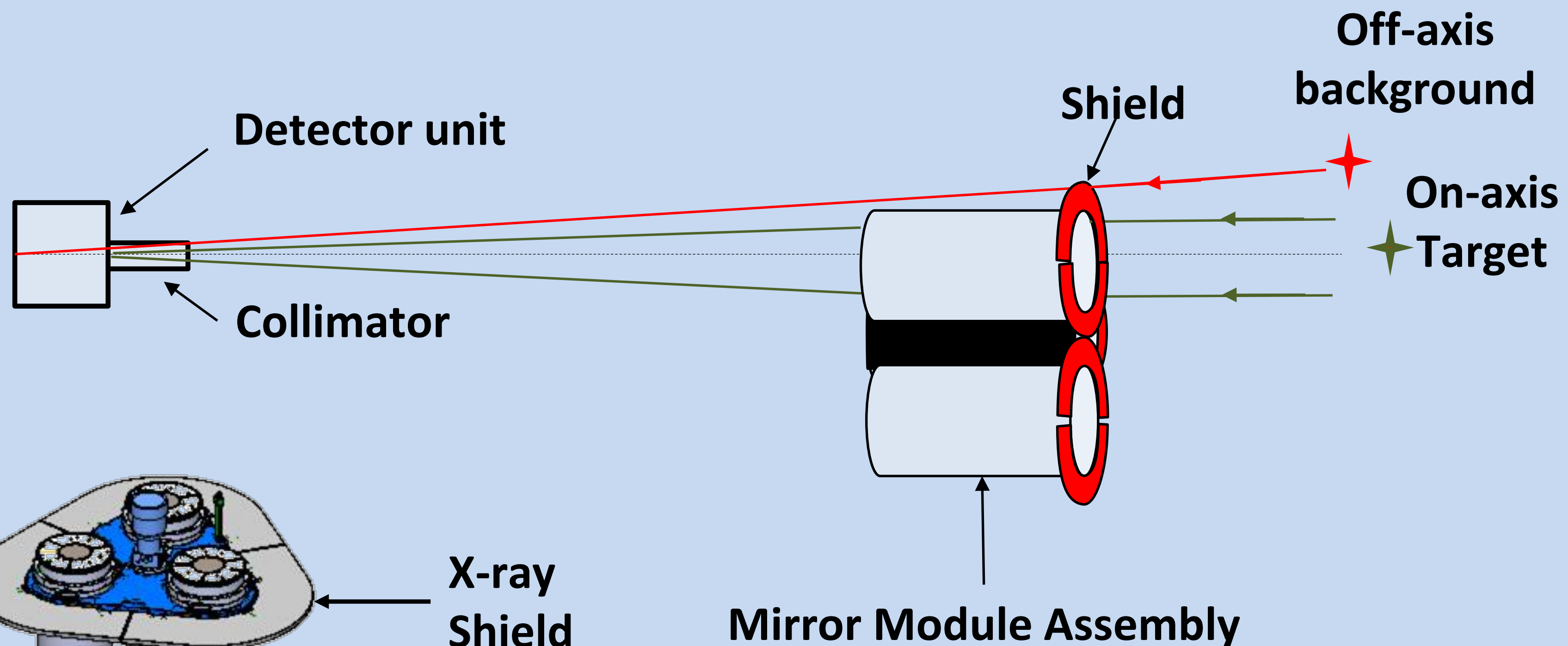
**Aft Star Tracker**

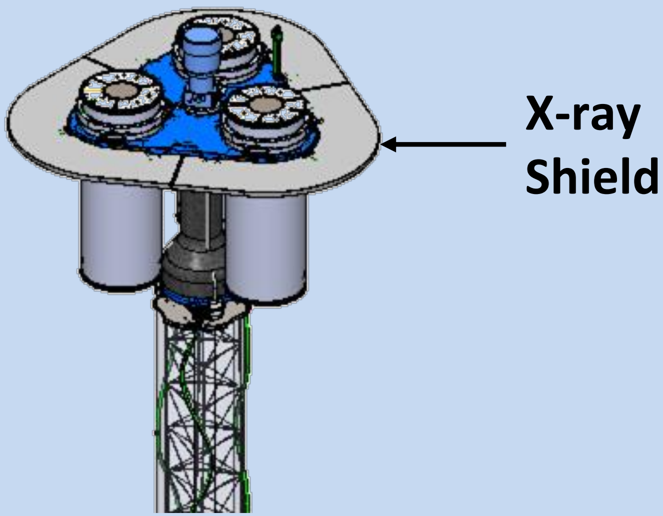


**Instrument thermal radiator**

**Folded solar panel (1 of 5)**

# *Shield and Collimator Suppress Background*



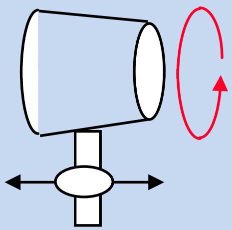



# *Optics Production*

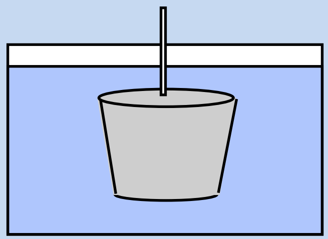
IXPE Imaging X-Ray Polarimetry Explorer

## Mandrel fabrication

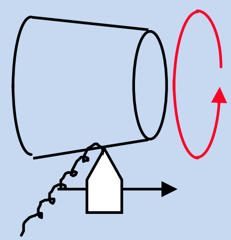
1. **Machine mandrel from aluminum bar**



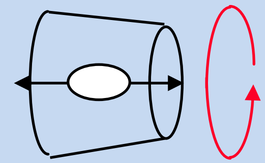
2. **Coat mandrel with electroless nickel (Ni-P)**



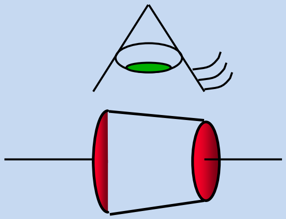
3. **Diamond turn mandrel to sub-micron figure accuracy**



4. **Polish mandrel to 0.3-0.4 nm RMS**

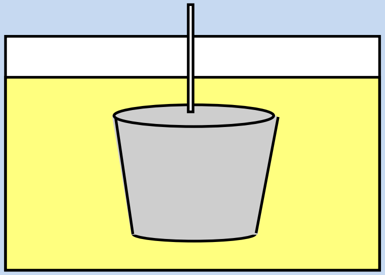


5. **Conduct metrology on the mandrel**

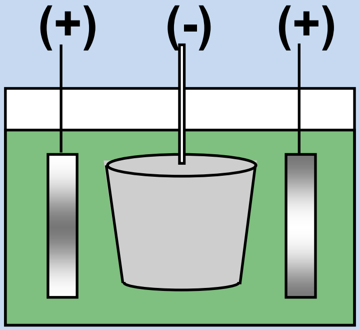


## Mirror-shell forming

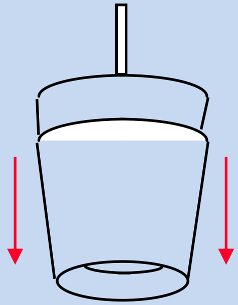
6. **Passivate mandrel surface to reduce shell adhesion**



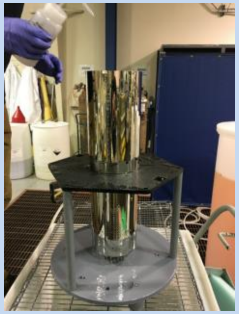
7. **Electroform Nickel/Cobalt shell onto mandrel**



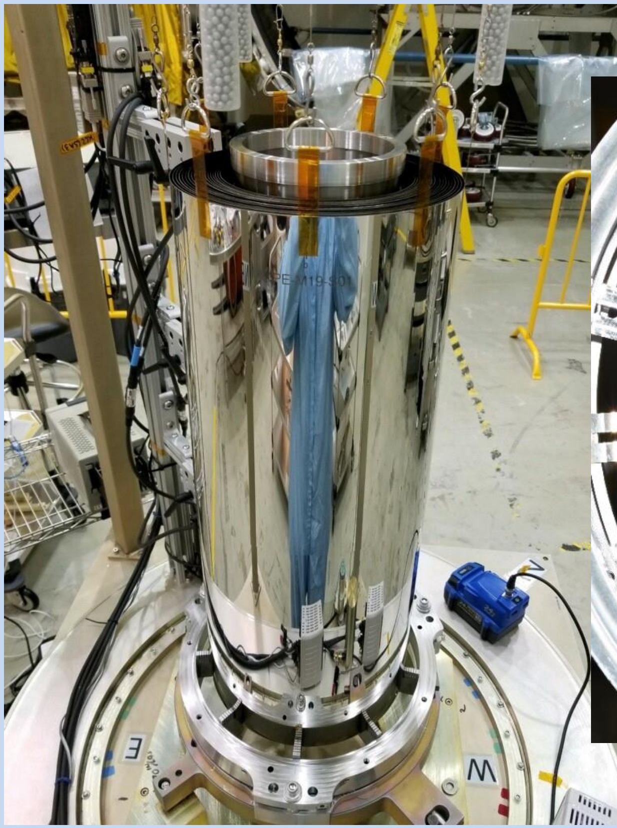

8. **Separate shell from mandrel in chilled water**

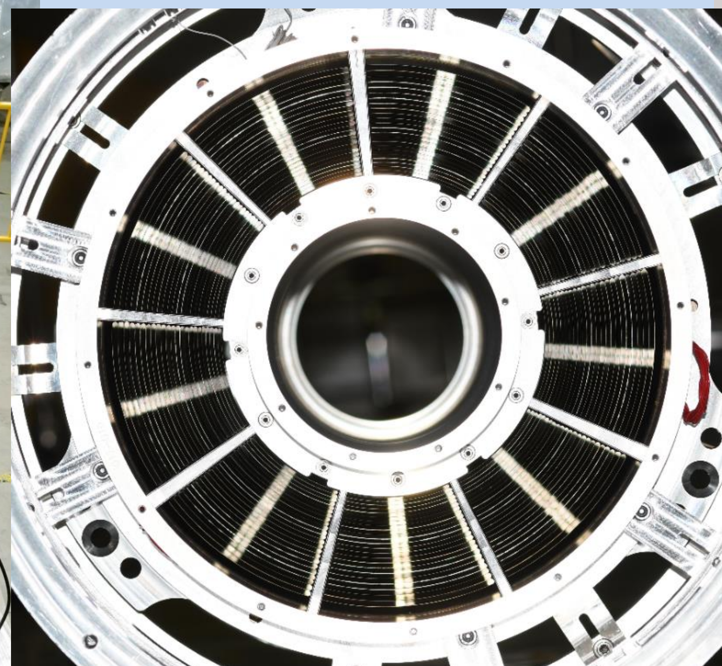


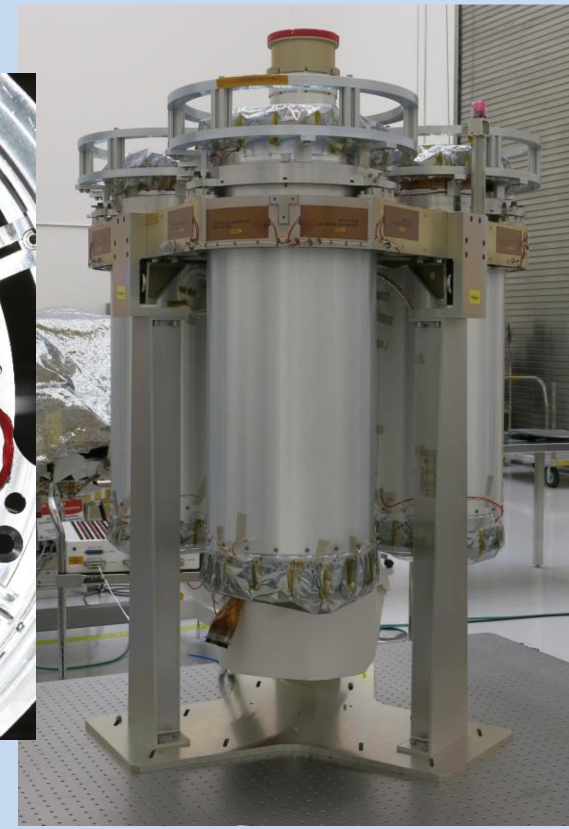
**Ni/Co electroformed IXPE mirror shell**



# *The Optics*

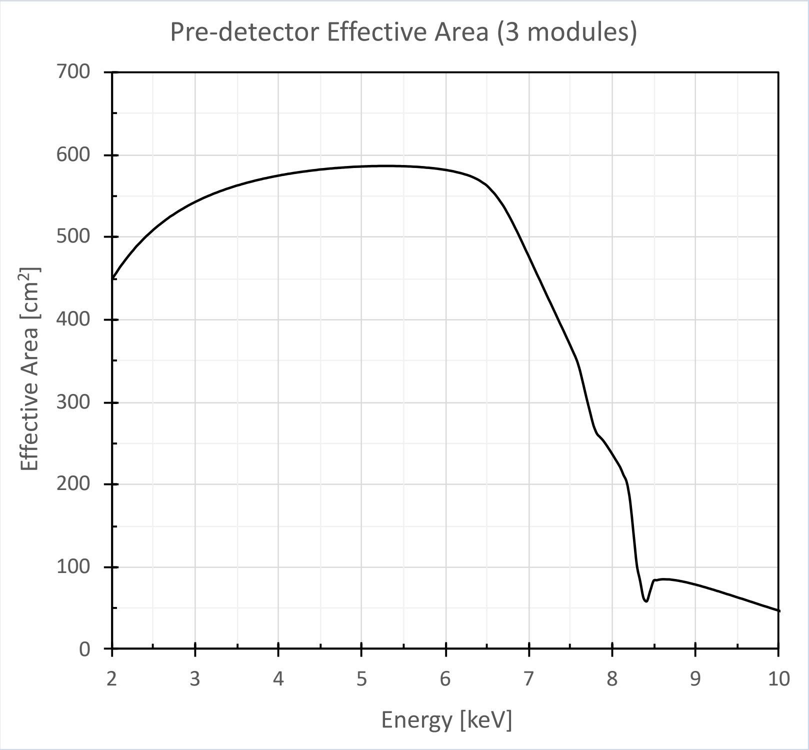






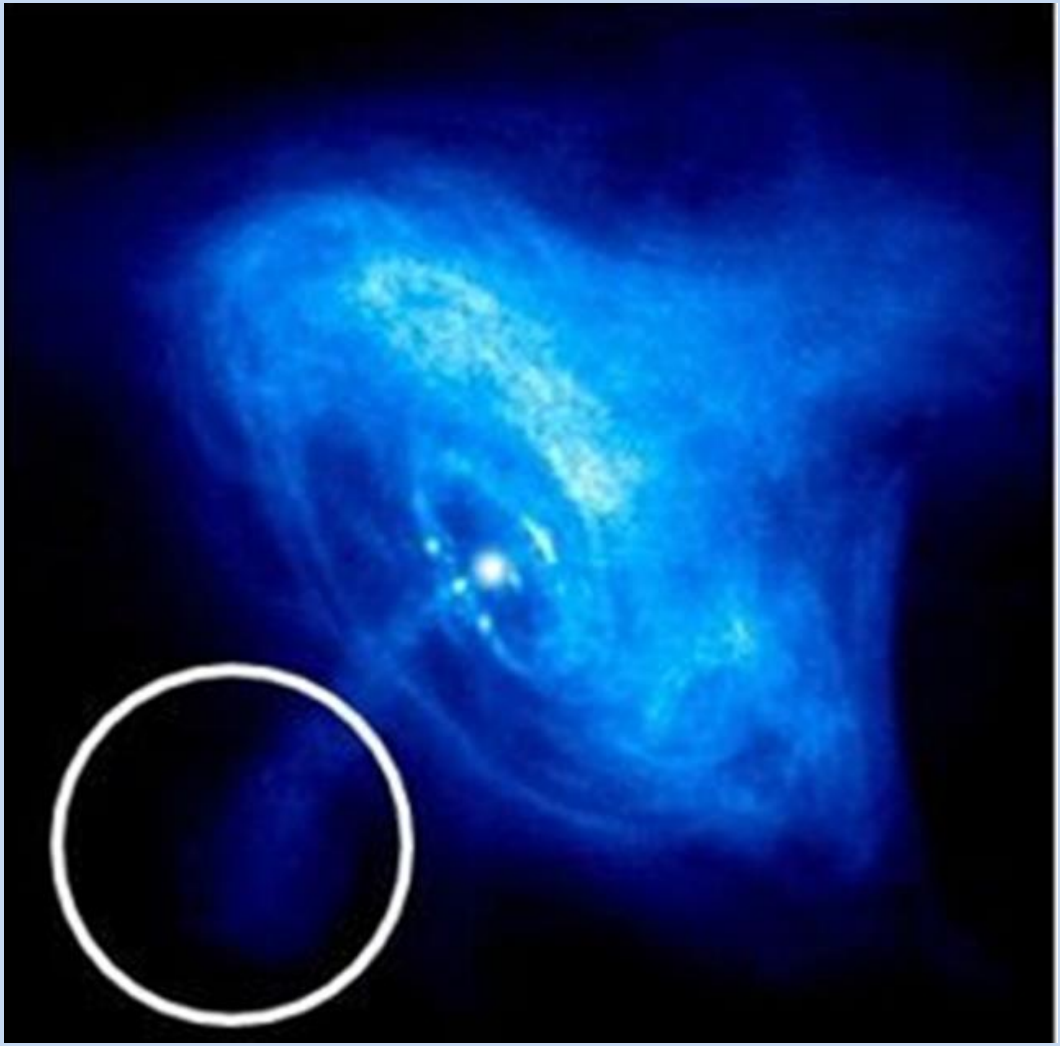
# Mirror Module Assembly Properties

| Property | Value |
|---|---|
| Number of modules | 3 |
| Mirror shells per module | 24 |
| Inner, outer shell diameter | 162, 272 mm |
| Total shell length | 600 mm |
| Inner, outer shell thickness | 180, 250 µm |
| Shell material | Nickel cobalt alloy |
| Effective area per module | 163 $cm^2$ (2.3 keV)<br>~ 192 $cm^2$ (3-6 keV) |
| Angular resolution | ≤ 27 arcsec HPD |
| Detector limited FOV | 12.9 arcmin |
| Focal length | 4 m |
| Mass (3 assemblies) | 93.12 kg |



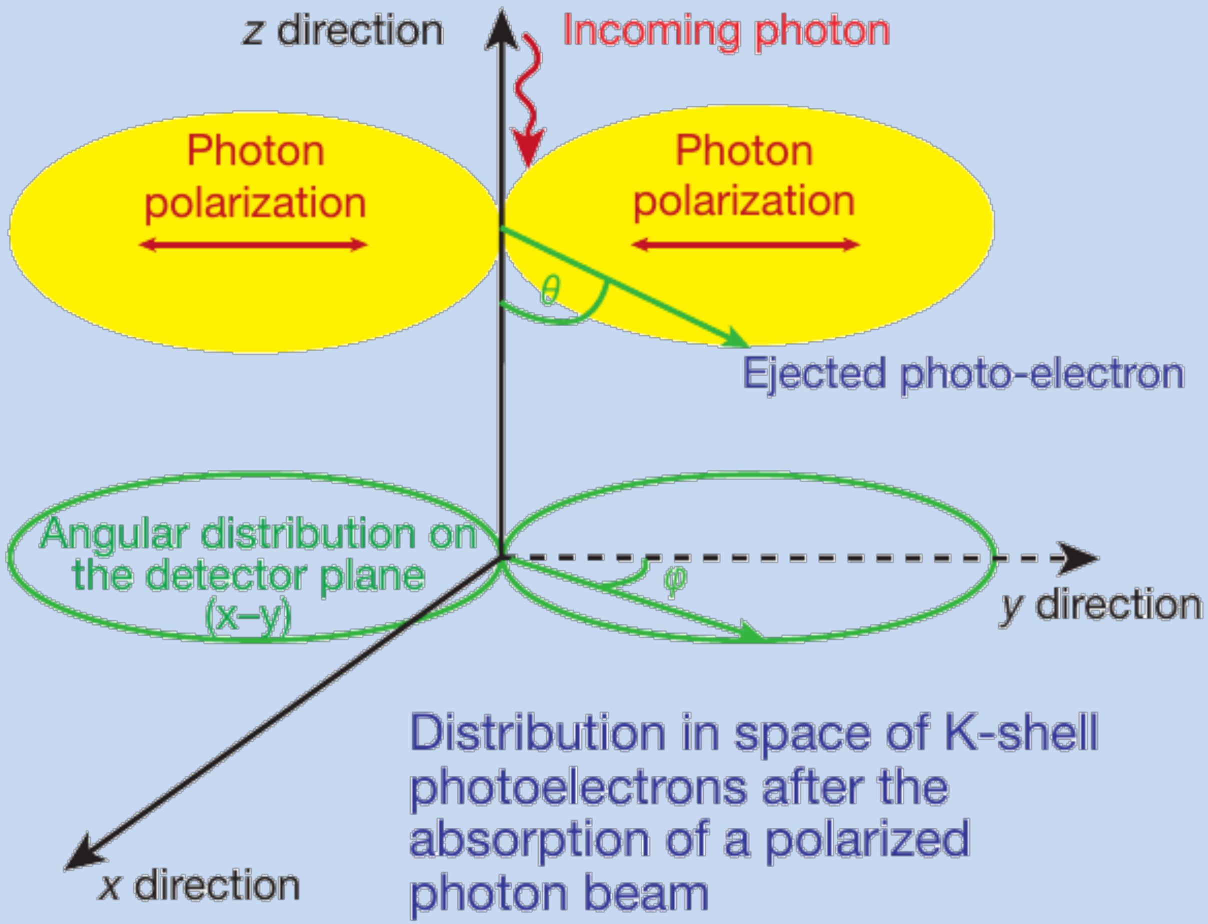
# *Imaging polarimetry*

- **IXPE 30” half-power diameter on Chandra image**

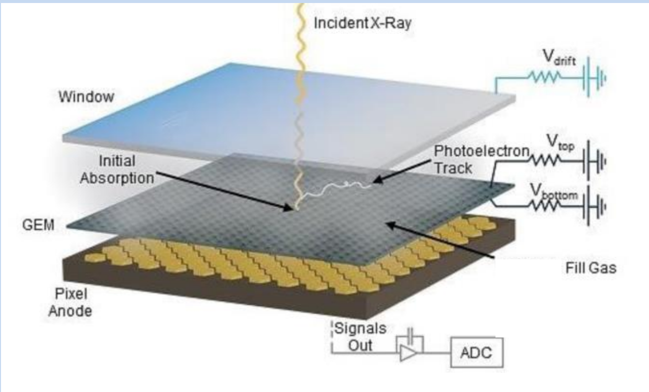


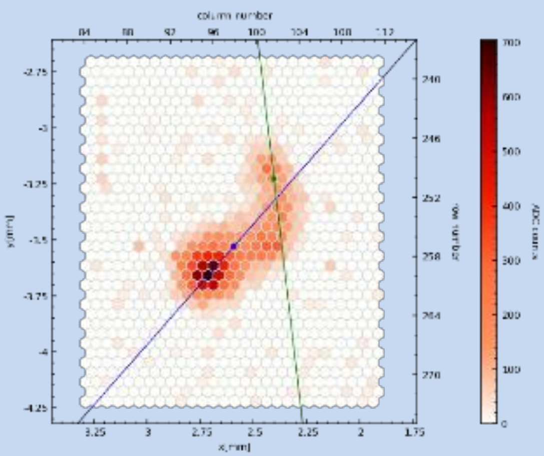
# *Polarization Detection Principle*

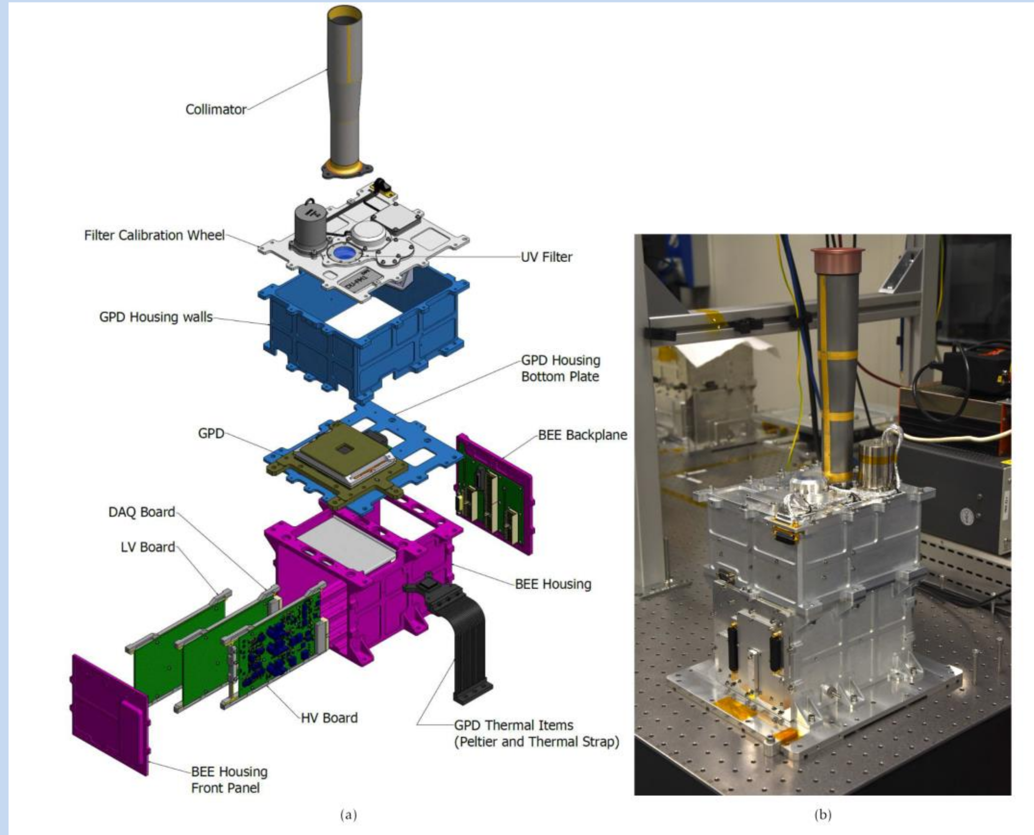
- **The detection principle is based on the photoelectric effect**



# The Polarization-Sensitive Detectors



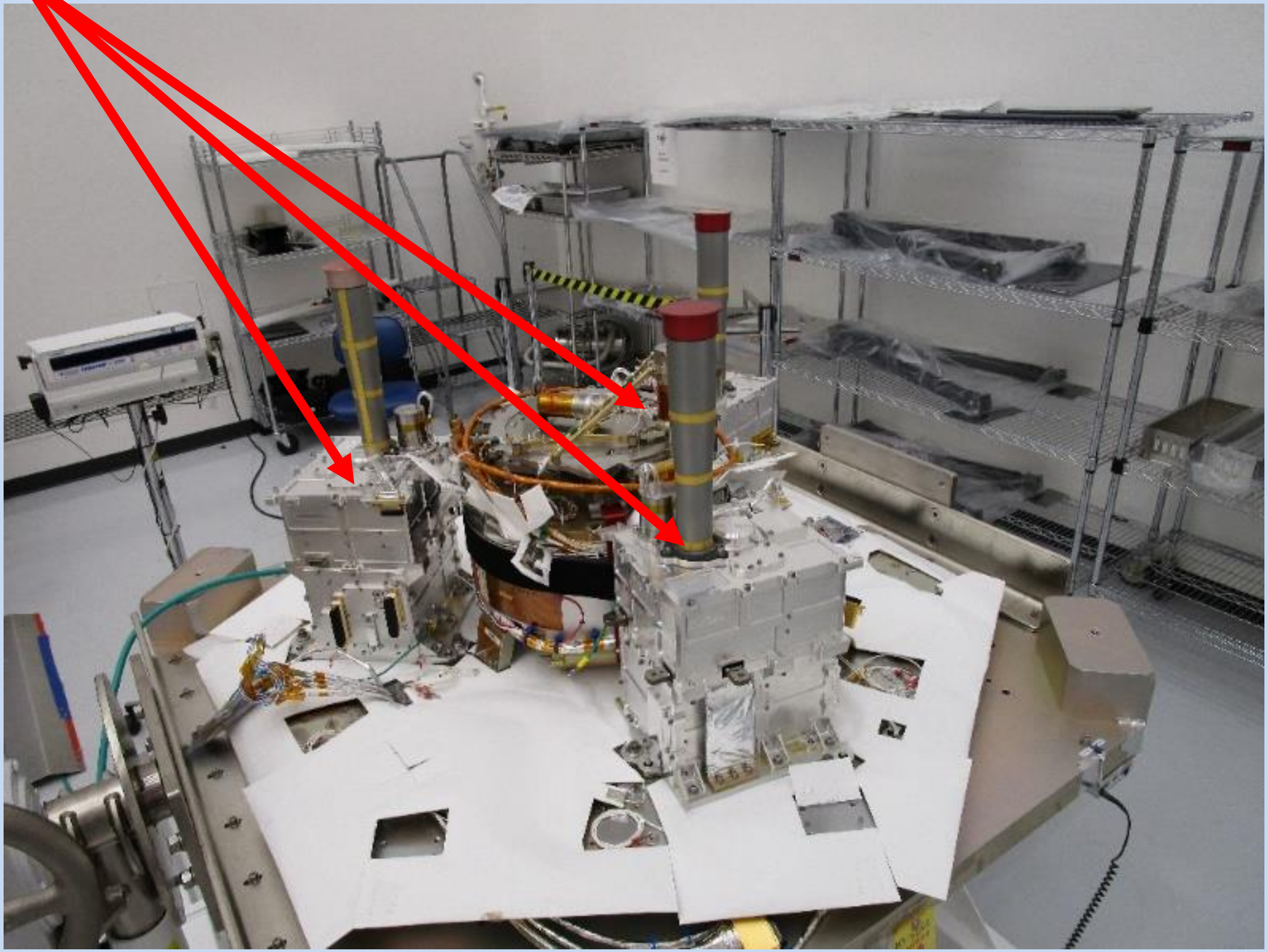




**The distribution of the photoelectron initial directions determines the degree of polarization and the position angle**

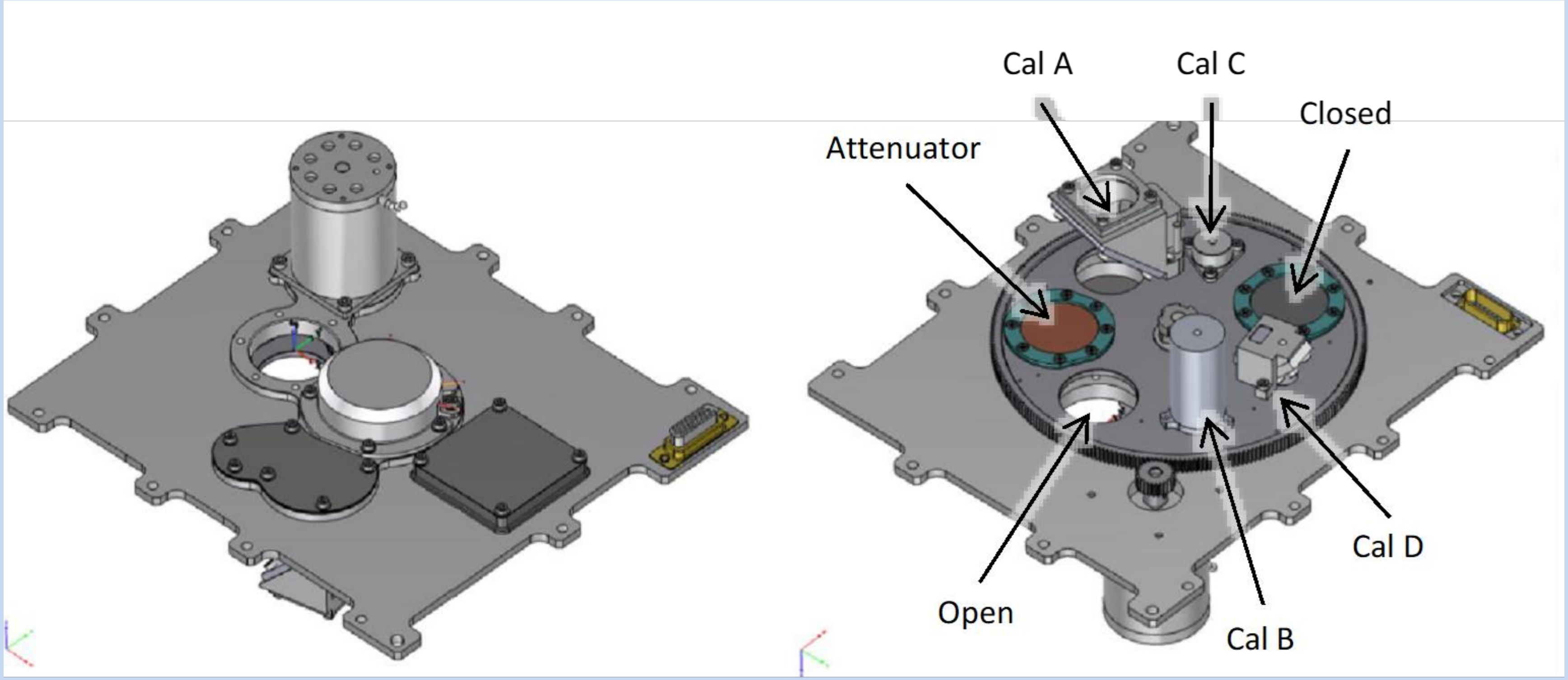
$$\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left(\frac{1}{\beta}\right)^{7/2} 4\sqrt{2}\sin^2\theta\cos^2\varphi\,, \text{ where } \beta \equiv \frac{E}{mc^2} = \frac{h\nu}{mc^2}$$

# The Detectors

- **The Detector Units (DUs) mounted to the spacecraft top deck at Ball**



# Filter Calibration Wheel Assembly




**Filter and Calibration Wheel (FCW), providing open, attenuator, and closed positions, plus four $^{55}$Fe-powered calibration sources:**

- **Cal A – Bragg-reflected polarized 2.98-keV (Ag-L$\alpha$ fluorescence) and 5.89-keV (Mn-K$\alpha$)**
- **Cal B – unpolarized 5.89-keV spot**
- **Cal C – unpolarized 5.89-keV flood**
- **Cal D – unpolarized 1.74-keV (Si-K$\alpha$ fluorescence) flood**

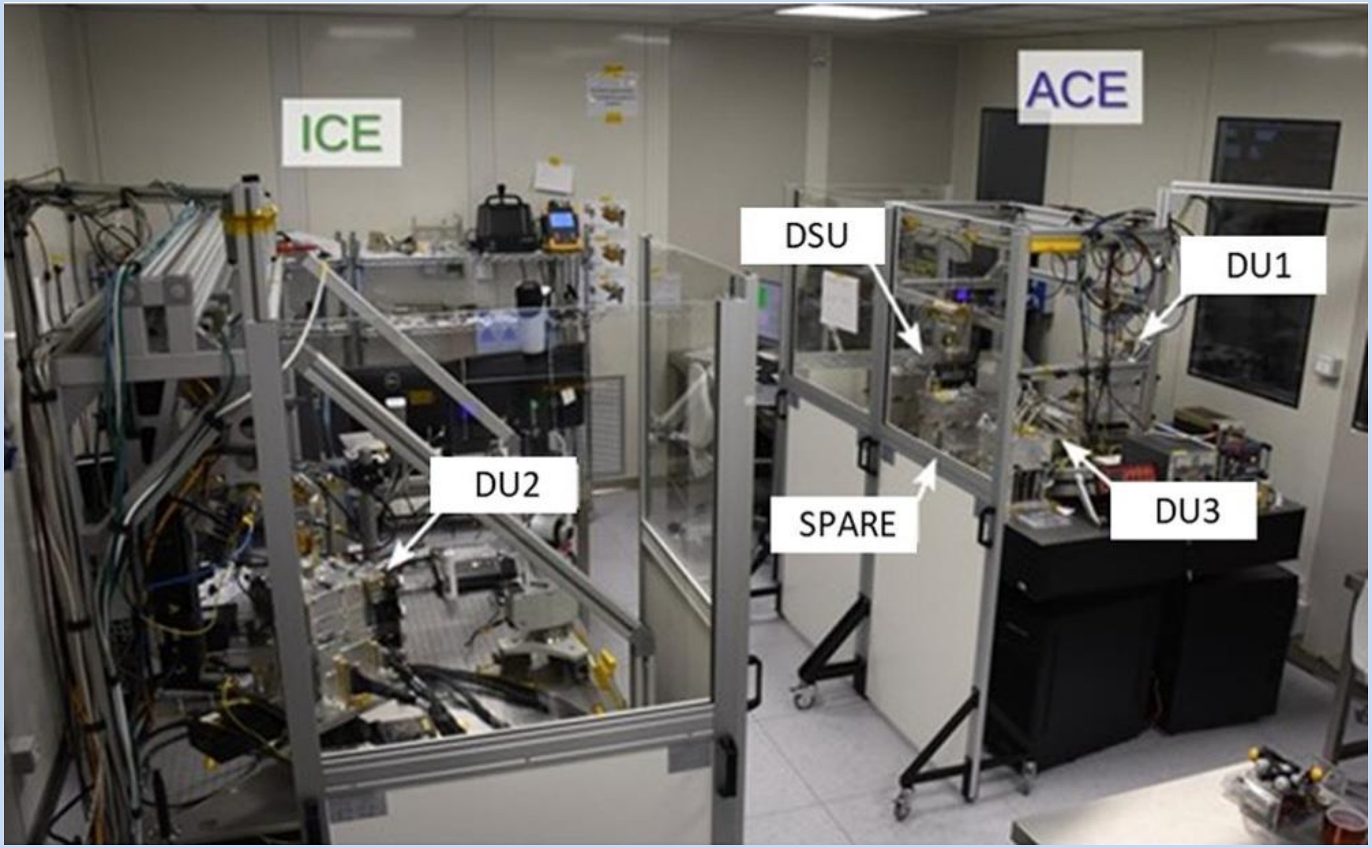
IXPE Imaging X-Ray Polarimetry Explorer

# Detector Properties

| Parameter | Value |
|---|---|
| Sensitive area | 15 mm × 15 mm (13 x 13 arcmin) |
| Fill gas and composition | DME @ 0.8 atmosphere |
| Detector window | 50-µm thick beryllium |
| Absorption and drift region depth | 10 mm |
| GEM (gas electron multiplier) | copper-plated 50-µm liquid-crystal polymer |
| GEM hole pitch | 50 µm triangular lattice |
| ASIC pixelated anode | Hexagonal @ 50-µm pitch |
| Number ASIC readout pixels | 300 × 352 |
| Spatial resolution (FWHM) | ≤ 123 µm (6.4 arcsec) @ 2 keV |
| Energy resolution (FWHM) | 0.57 keV @ 2 keV ($\propto \sqrt{E}$) |
| Useful energy range | 2 - 8 keV |

# On-Ground Calibration

- Detector Units calibrated in Italy using both polarized and unpolarized X-ray sources
- Mirror Module Assemblies calibrated at MSFC using both polarized and unpolarized sources
- One complete telescope (MMA+DU) also calibrated at MSFC

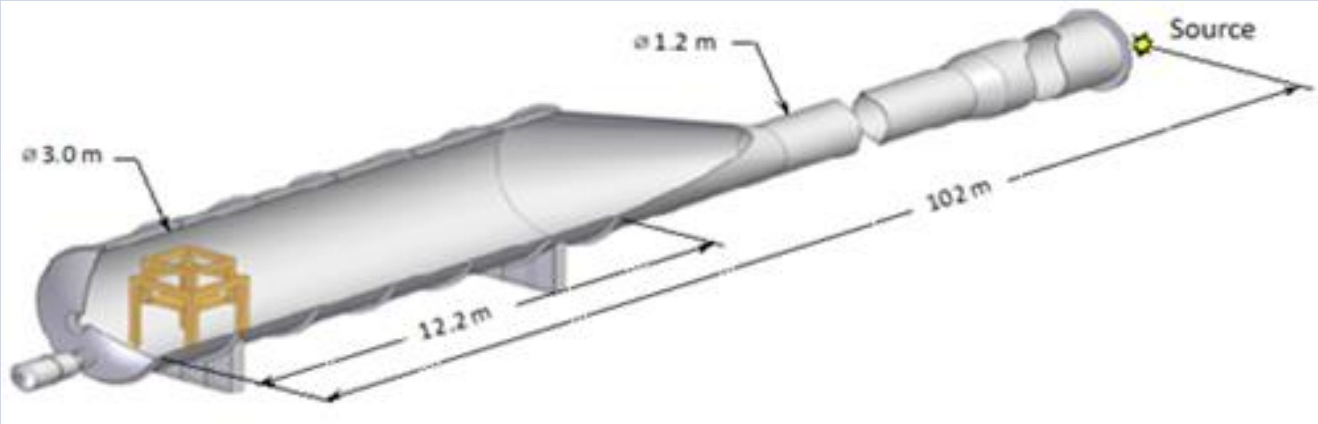


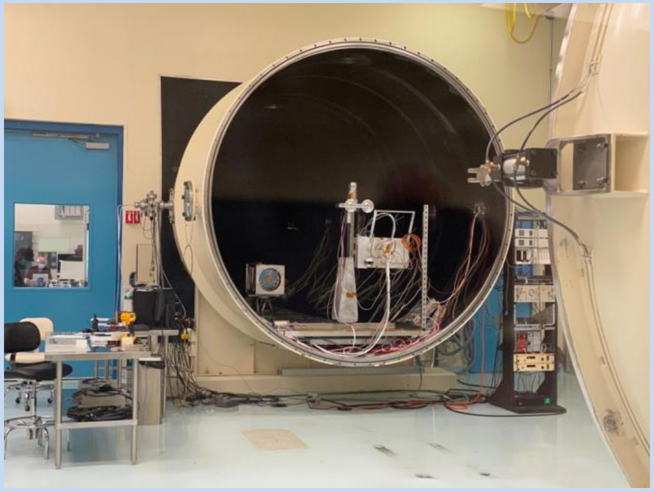

**Detector Service Unit (DSU)**

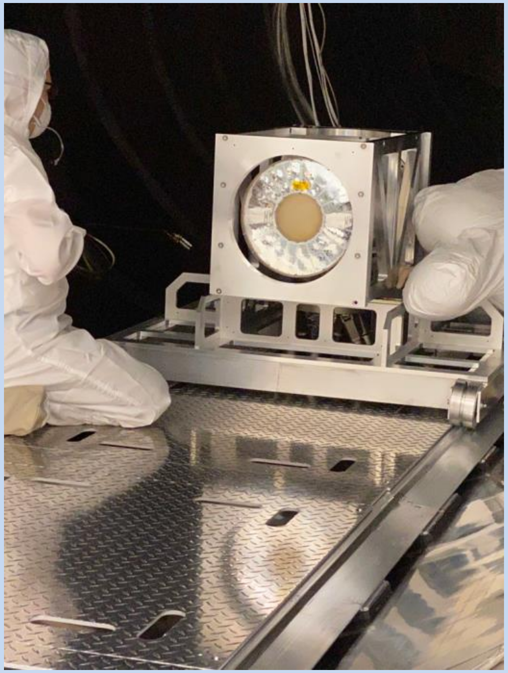
**instrument calibration equipment (ICE)**

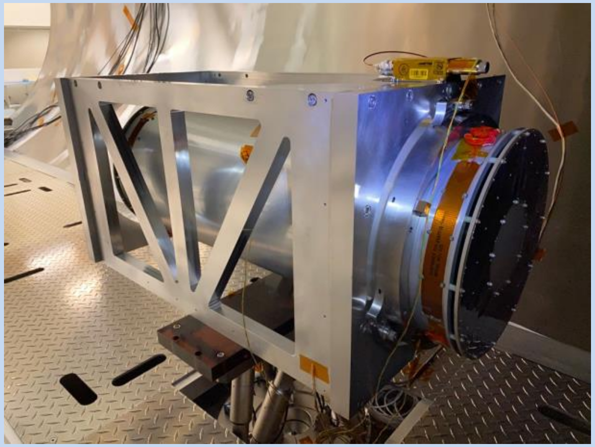
**assembly integration and verification test calibration equipment ACE)**

# MSFC "Stray Light" X-ray Test Facility

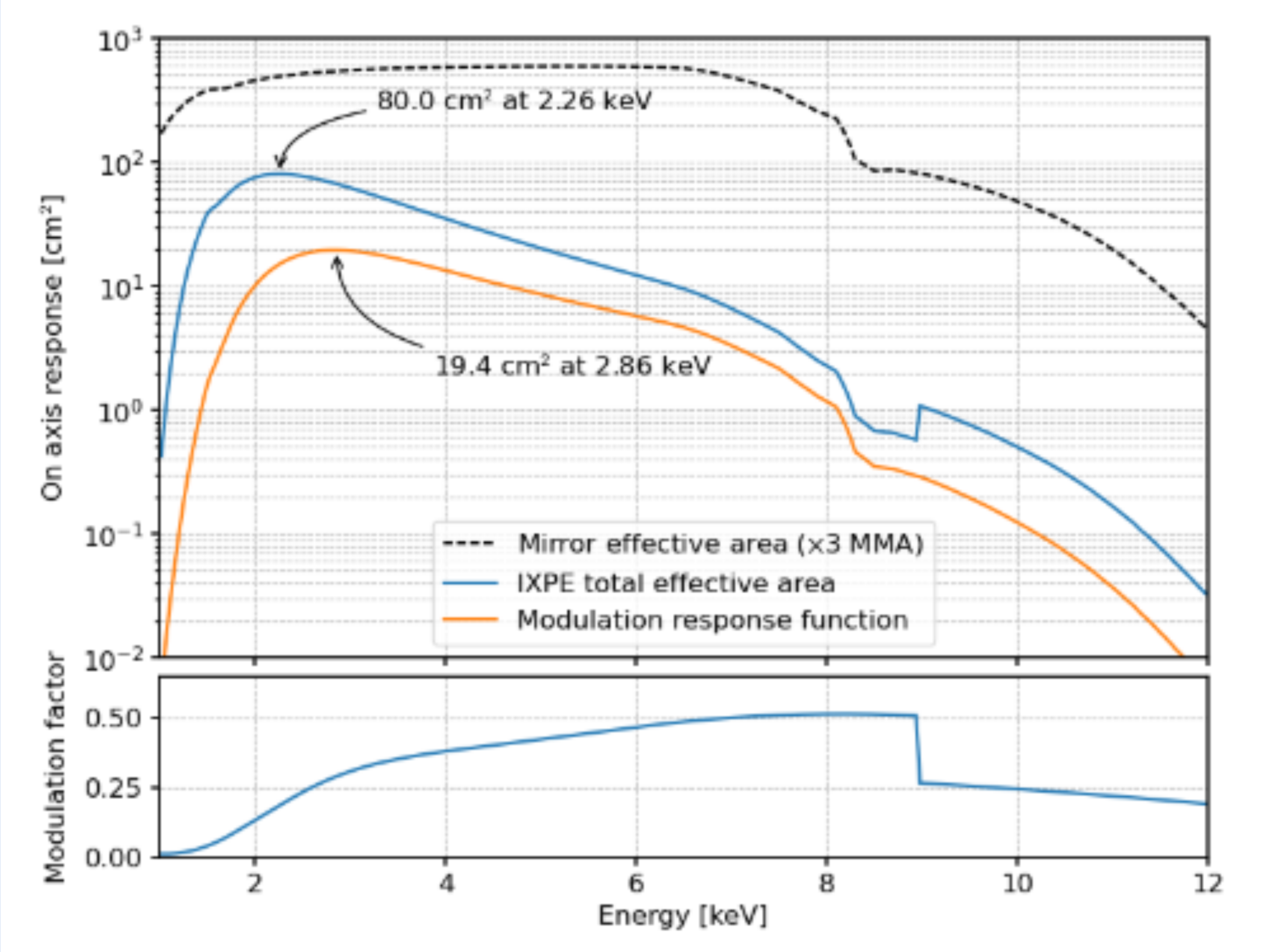






# Effective Area and Modulation Factor

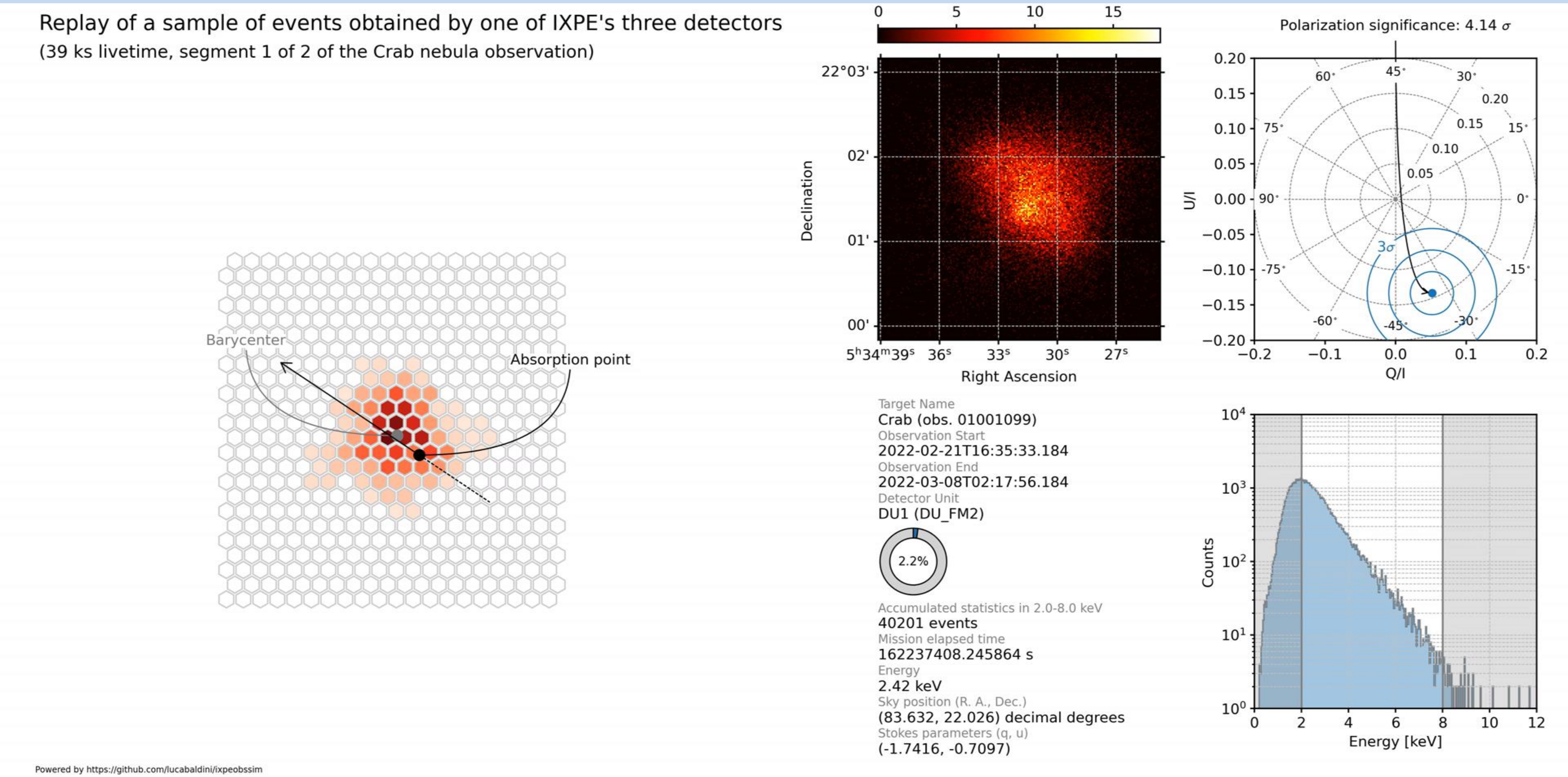


# *The Minimum Detectable Polarization (MDP)*

$$MDP_{99}(\%) = (4.29x10^4 / M(\%))\sqrt{(R_S + R_B)} / \sqrt{R_S^2 t}$$

- $R_S$ **is the observed source counting rate**
- $R_B$ **is the observed background counting rate**
- ***t*** **is the integration time**
- ***M*** **is the modulation factor, i.e. the amplitude of the variation of the ensemble of position angles for a 100% polarized source**

# How it Works: Observing the Crab Nebula



# *The Early Results*

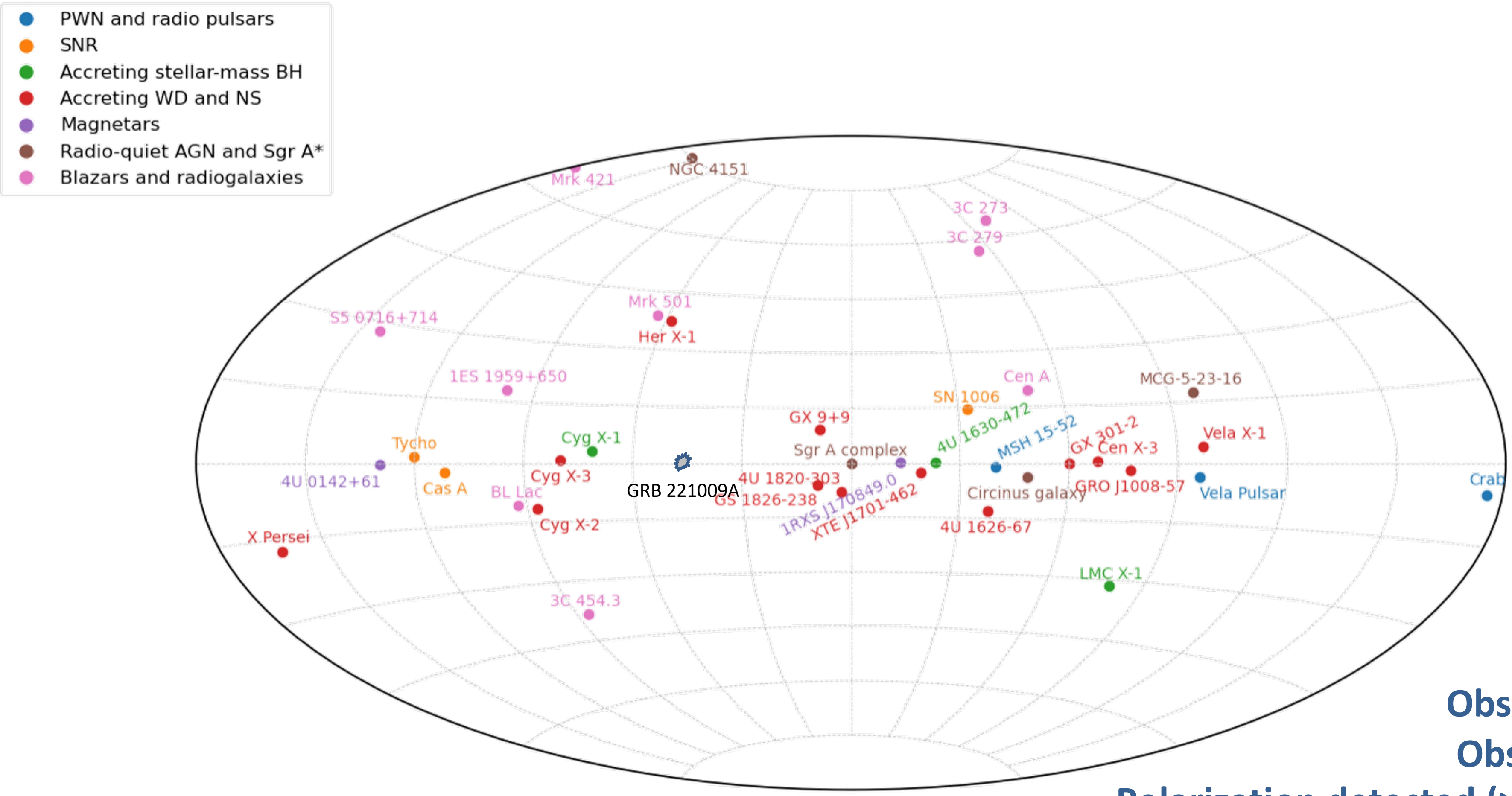
- IXPE's first observations have been *especially* rewarding with many leading to unexpected results
  - See the following talks for details

# The Imaging X-ray Polarimetry Explorer (IXPE)
# Science Results One Year Post-Launch


**Steven Ehlert, IXPE Project Scientist**
**(NASA Marshall Space Flight Center)**
***on behalf of the IXPE Science Team***

# Year-1 Targets

## IXPE's first year of observations has resulted in many new discoveries about familiar X-ray sources




***2022 December 8***

**Sources observed: 39**

**Observations completed: 54**

**Observations processed: 52**

**Polarization detected (> 99.99% confidence): 19**

# IXPE Science

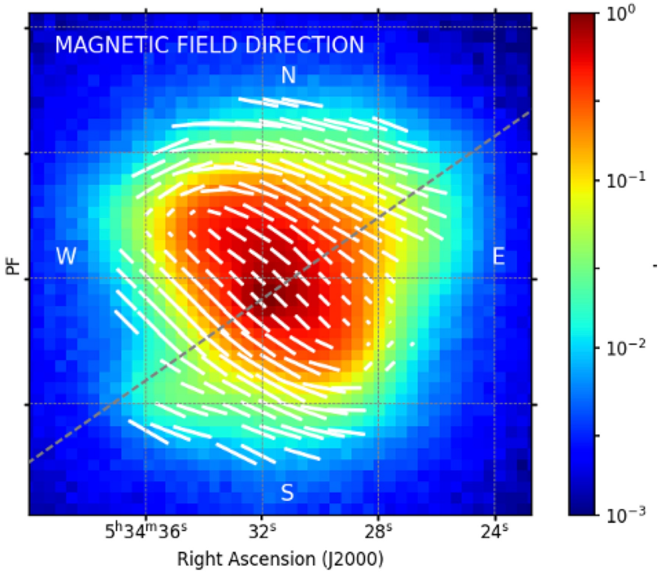
**IXPE Science is divided up into seven different topical working groups (TWG's):**

1. Pulsar Wind Nebulae and Radio Pulsars
2. Supernova Remnants
3. Accreting Stellar Mass Black Holes
4. Accreting White Dwarf and Neutron Stars
5. Magnetars
6. Radio Quiet Active Galactic Nuclei and the Galactic Center
7. Blazars and Radio Galaxies

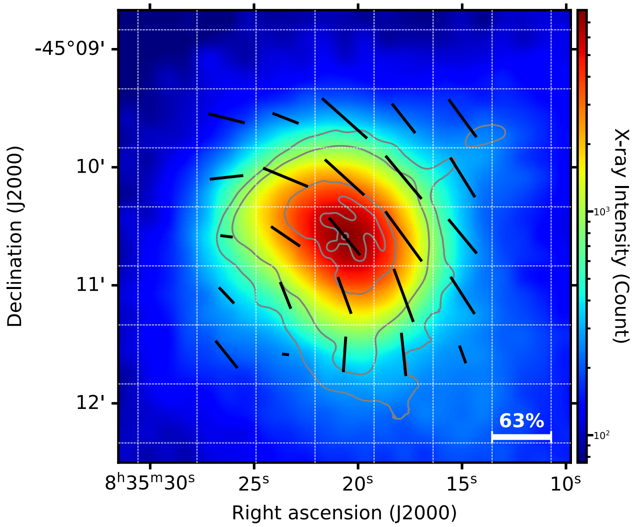
# Pulsar Wind Nebulae

IXPE images

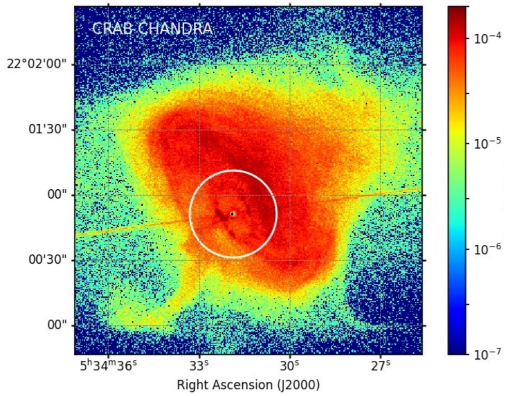
20% average, 48% peak polarization
Toroidal magnetic field structure



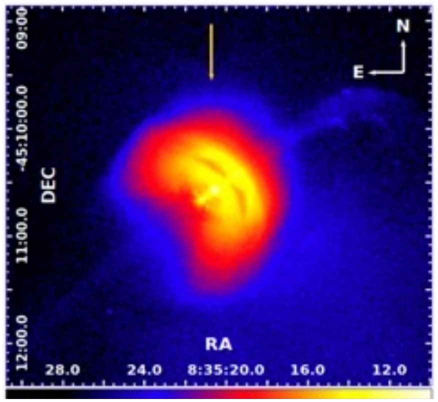

45% average, 63% peak polarization
Toroidal magnetic field structure




Chandra images




Crab pulsar wind nebula

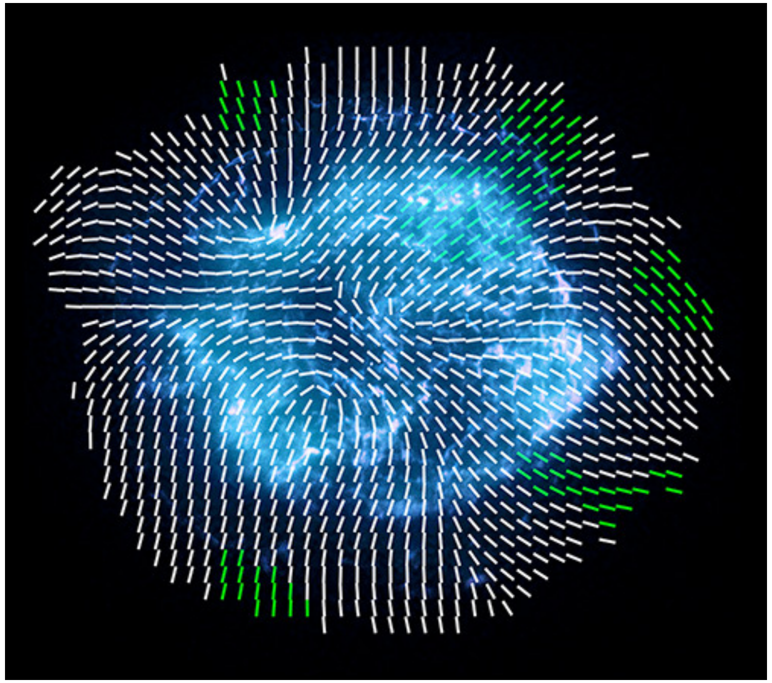


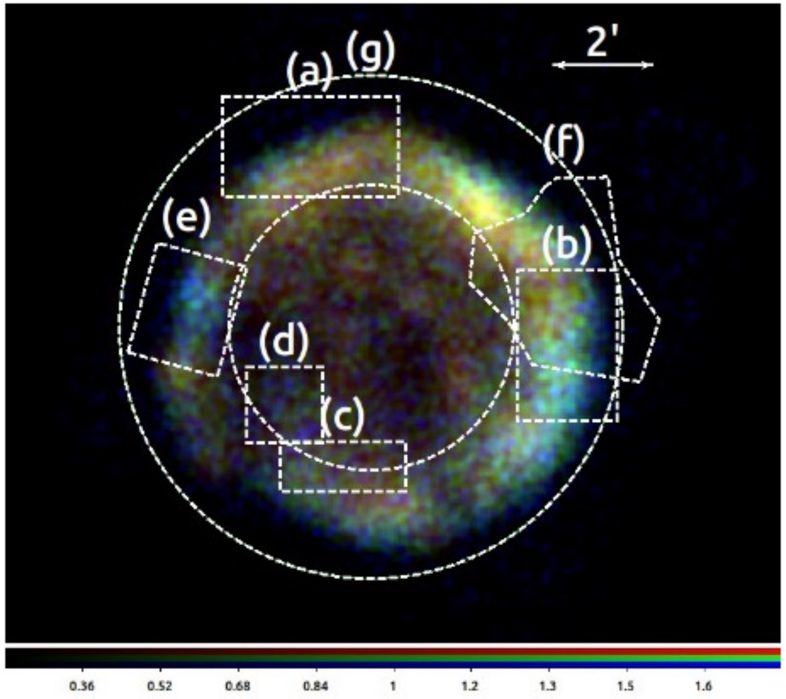

Vela pulsar wind nebula

**IXPE has shown that pulsar wind nebulae are sources of highly ordered magnetic fields, with polarization degrees approaching the limits for synchrotron radiation**

Crab: Bucciantini et al, submitted to Nature Astronomy
Vela: Xie et al, Nature

# IXPE has measured the presence of radial magnetic fields and the maximum scale length of turbulence in two supernova remnants

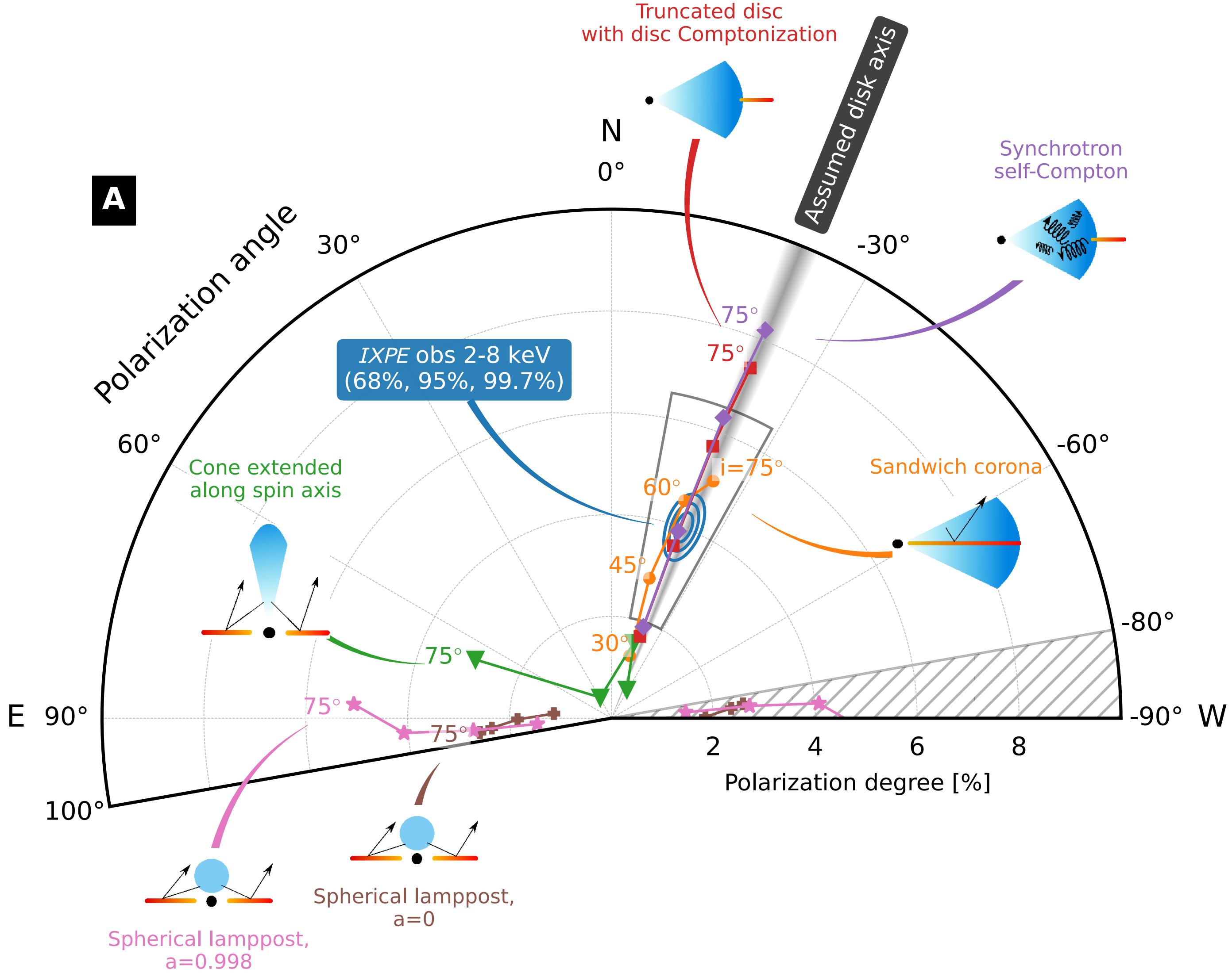





$Cas\ A$: $\Pi = (1.8 \pm 0.3)$ % azimuthal angle
$\lambda \sim 10^{17}\ cm$
Vink et al, Astrophysical Journal

$Tycho$: $\Pi = (9.1 \pm 2.1)$% azimuthal angle
$\lambda \sim 10^{18}\ cm$
Ferrazzoli et al, Astrophysical Journal

# Accreting Stellar Mass Black Holes



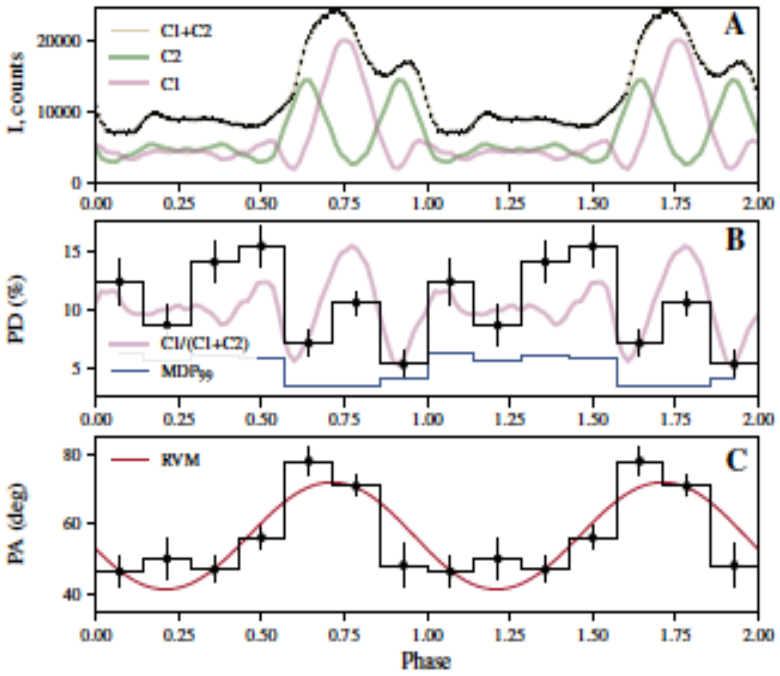

**Polarization measurements from IXPE provide essential information about the geometry of the X-ray emitting region in low-mass X-ray binaries such as Cygnus X-1**

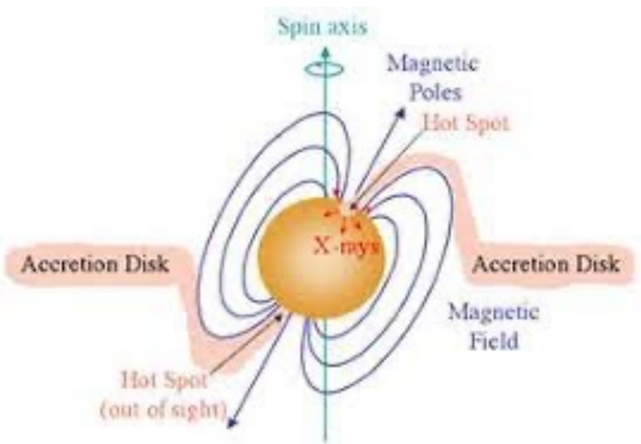
$\Pi = (4.0 \pm 0.2)\%$ $\quad \psi = (-20.7 \pm 1.4)°$

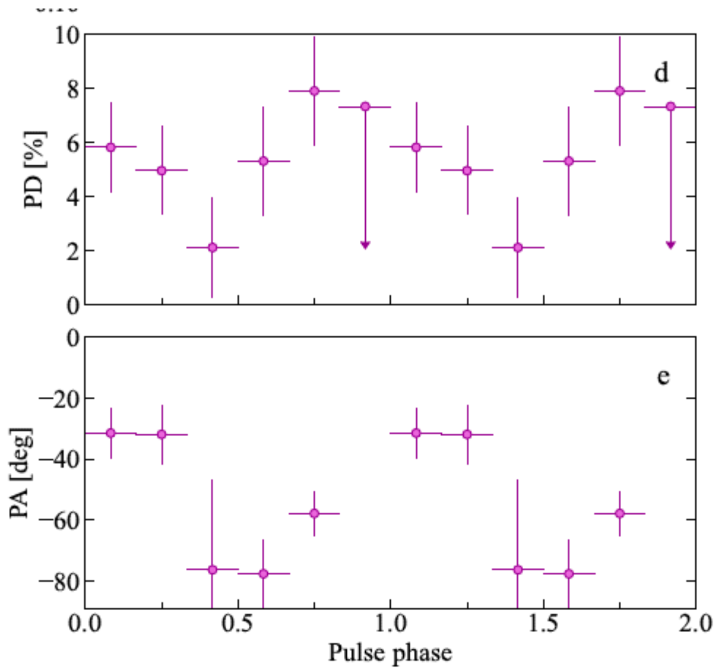
Krawczynski et al, Science

# Accreting Neutron Stars

**Accreting neutron stars have shown much lower polarization degrees than models predicted, suggesting the need for major changes to our understanding of these objects.**




$Her\ X-1\colon\ \Pi = (8.6 \pm 0.5)\%\quad \psi = (+62 \pm 2)^\circ$

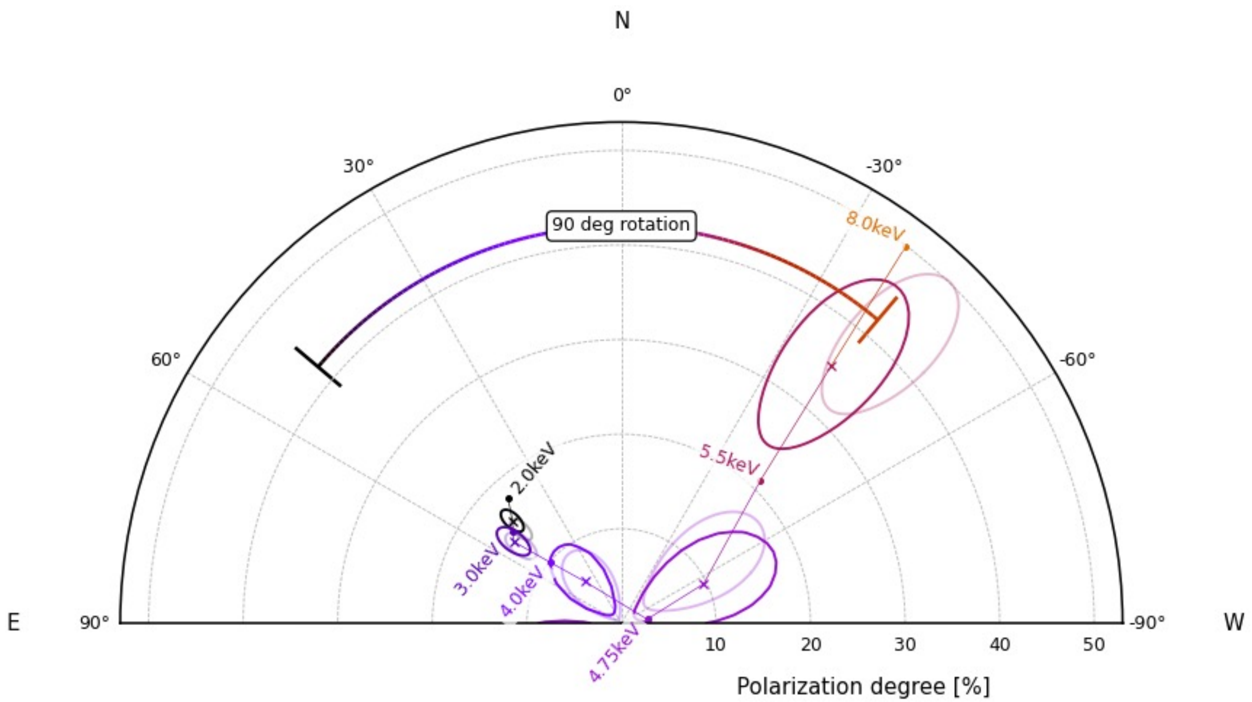
Doroshenko et al, Nature Astronomy

$Vela\ X-1\colon\ \Pi = (3.9 \pm 0.9)\%\quad \psi = (-52 \pm 7)^\circ$

Forsblom et al, submitted to ApJ Letters

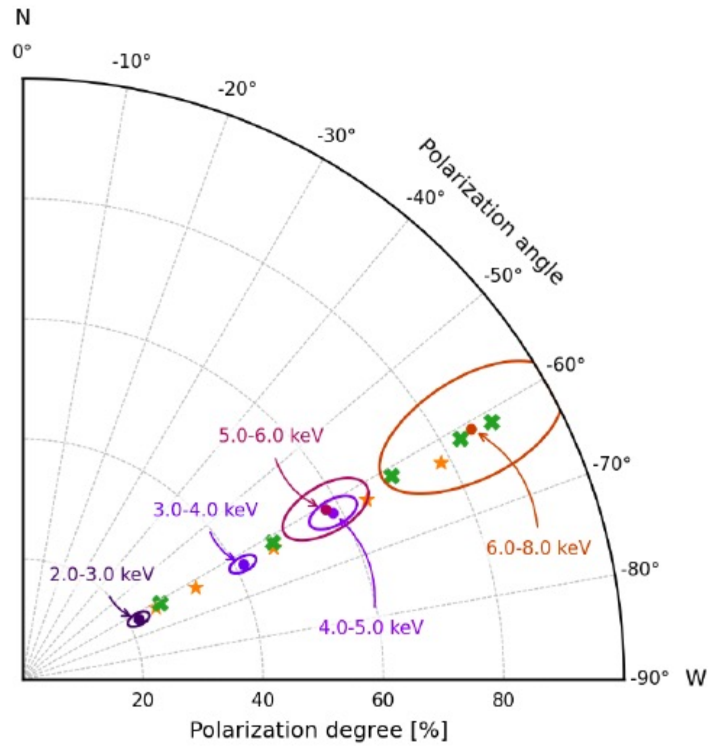
# Magnetars

## IXPE observations of magnetars show evidence of the exotic physics predicted from their extremely high magnetic fields




$\Pi = (13.5 \pm 0.8)\%$ $\psi = (+48.5 \pm 1.6)°$

Taverna et al, Science

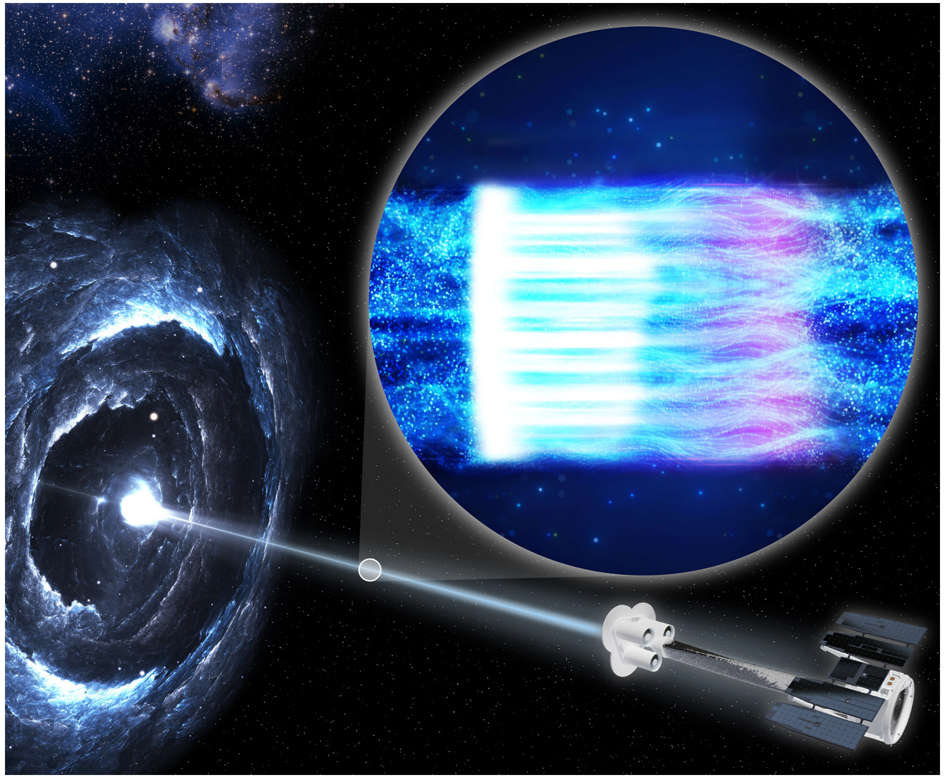



$\Pi = (35.1 \pm 1.3)\%$ $\psi = (-62.1 \pm 1.3)°$

Zane et al, accepted ApJ

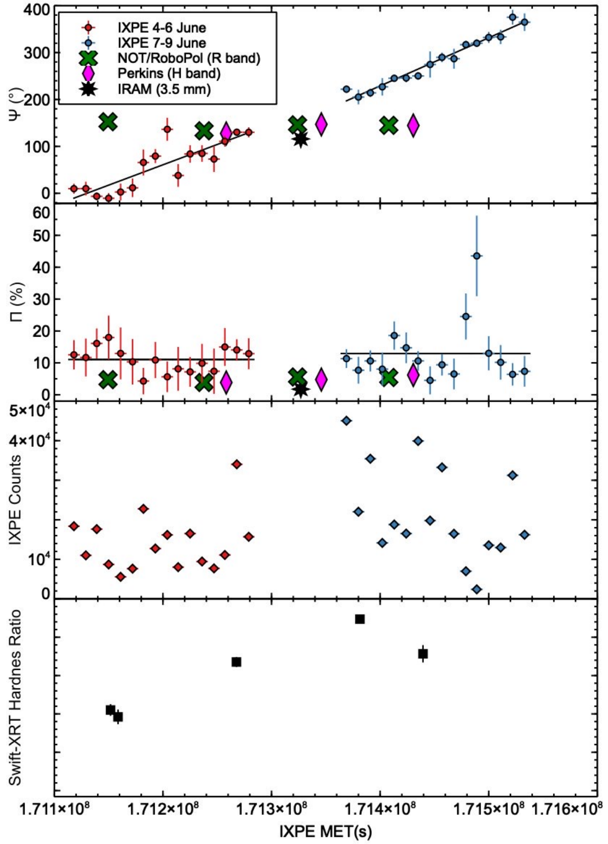
# Blazars and Radio Galaxies: High Synchrotron Peak

**Observations of blazars with synchrotron peaks in the IXPE bandpass show compelling evidence of energy-stratified shock acceleration that can vary with time**



$Mrk\ 501$: $\Pi = (10 \pm 2)\%$ $\quad \psi = (-45 \pm 5)°$

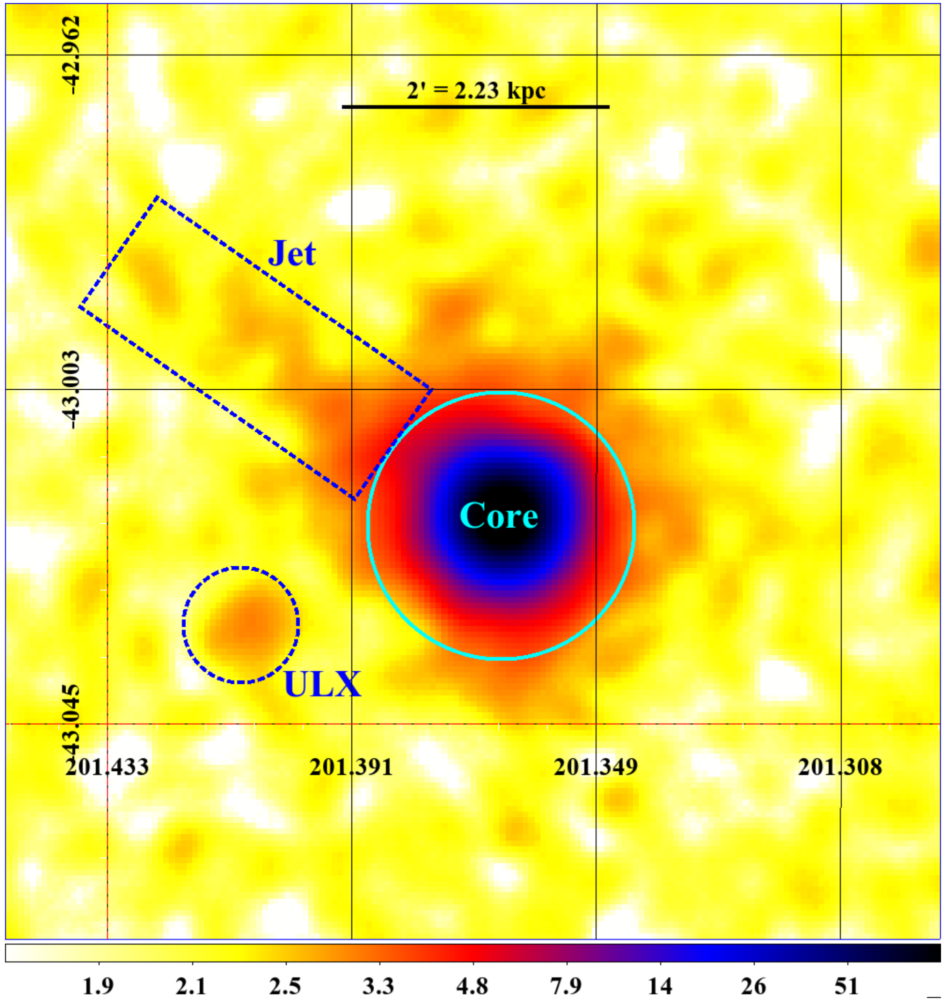
Liodakis et al, Nature




$Mrk\ 421$: $\Pi = (10 \pm 1)\%$ $\quad \psi' = (77 \pm 2.4)°/day$

Di Gesu et al, in prep

# Blazars and Radio Galaxies: Low Synchrotron Peak



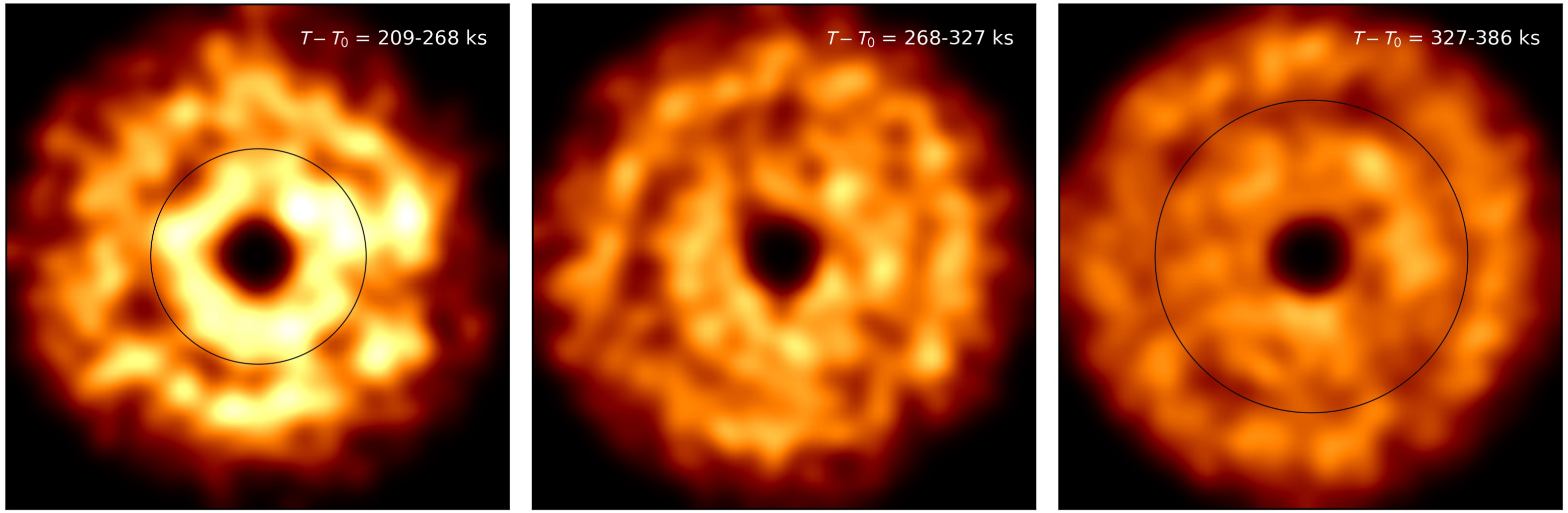

**For AGN jets where only upper limits can be measured, IXPE can nevertheless place important constraints on how particle acceleration operates in these systems.**

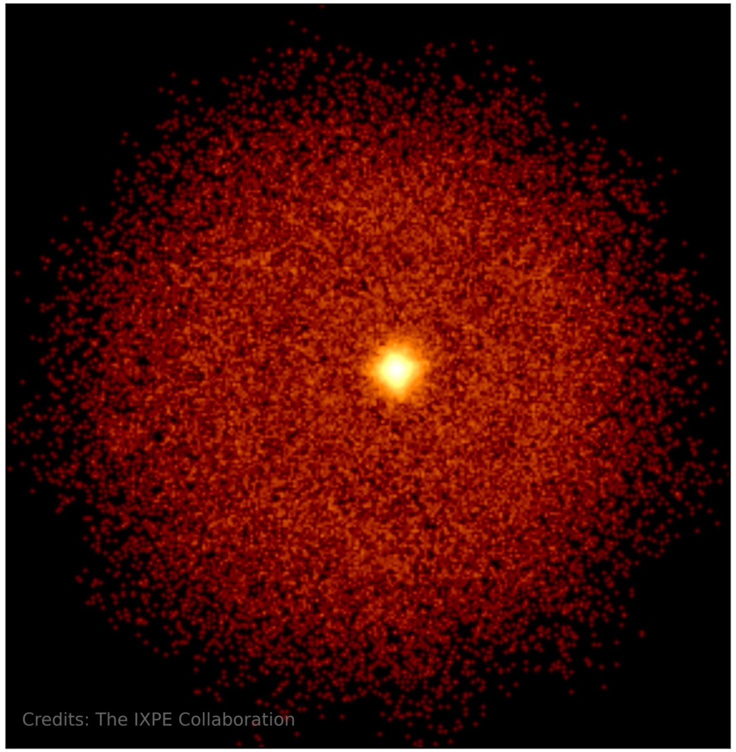
$Cen\ A$: $\Pi < 6.5\%$. Ehlert et al, Astrophysical Journal

$BL\ Lac$: $\Pi < 14\%$. Middei et al, accepted MNRAS

# Target of Opportunity: The BOAT

**IXPE was able to observe GRB 221009A, the brightest gamma-ray burst to encounter Earth since we have had gamma-ray detectors**




$Core\ (Afterglow)\!:\ \Pi < \ 13.8\%$
$Rings\ (Prompt)\!:\ \Pi < 55 - 82\%$
Negro et al, ApJ Letters accepted